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A Qualification study and assessment of the CO_2 storage capacity, siting and costs in Portugal

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Abstract

CCS has the potential to act as a bridge reducing CO_2 emissions now as the world moves to renewable sources of energy. Yet questions over the security of CO_2 storage and the cost of large scale deployment remain. This work looks at the key technoeconomical issues which arise in CO_2 storage, including the characterization of possible storage sites - one of the main targets of this work - with the principal focus to describe candidate CO_2 storage reservoirs and the process by which CO_2 could be injected and stored in these formations. A thorough evaluation of these formations and their ability to accept and retain injected CO_2 must be an essential component of site assessment before any CO_2 is injected. Here we take a closer look at these formations in the broad area of Portugal and try to match the potential sites with the greater CO_2 emissions power plants. At a properly designed and well-managed CO_2 storage site, the chance of CO_2 leakage should be small; thus, concerns about catastrophic release are likely unfounded.

Keywords: CO_2; storage; capacity; sites; Portugal.

1. Introduction

Energy use and energy generation are at the heart of the global climate change and GHG emissions problem, with the International Energy Agency (IEA) forecasting that global electricity generation will nearly double from 2005 to 2030. Presently more than 80% of the world´s energy is coming from fossil fuel while the IEA says that fossil fuels will remain a significant part of the energy mix up to 2030, comprising roughly 70% of global and 60% of European electricity generation. Carbon Capture and Storage (CCS) technologies are increasingly seen as critically important elements of a global portfolio of advanced energy technologies needed to address climate change. One sign of the

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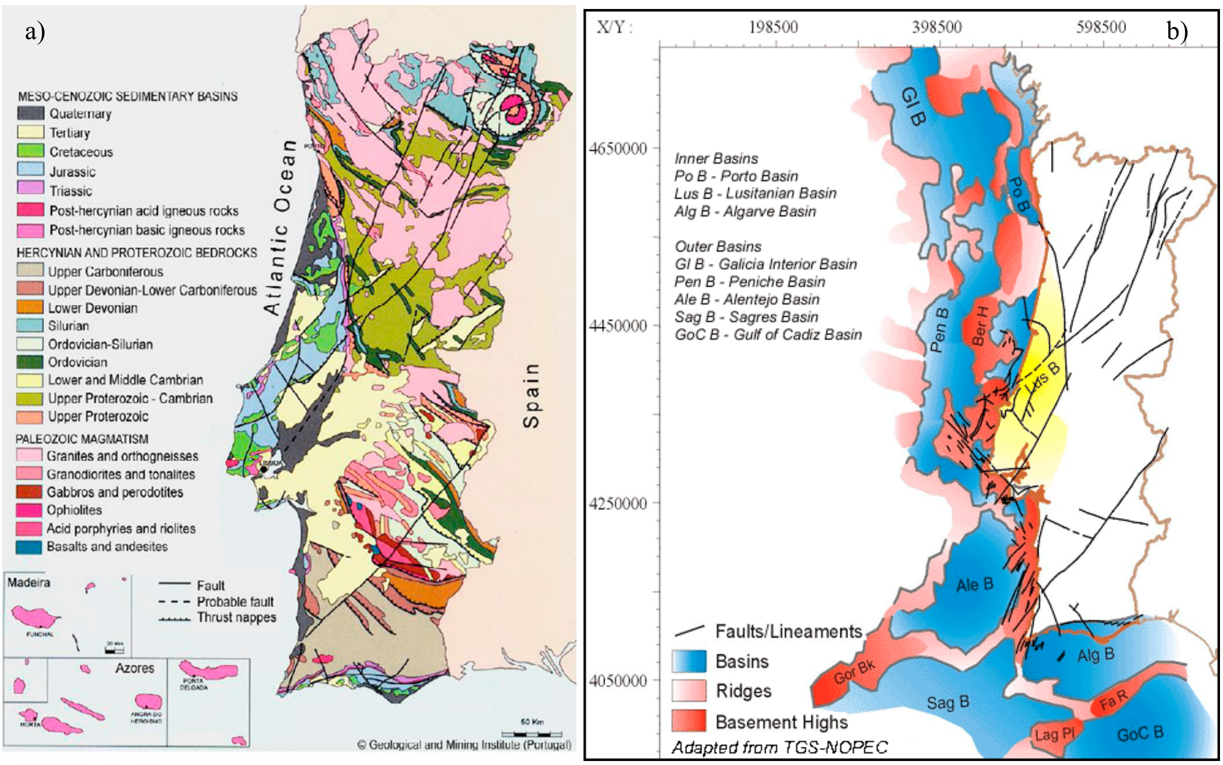
significant interest in CCS technologies has been the publication of the Intergovernmental Panel on Climate Change's *Special Report on Carbon Dioxide Capture and Storage* [1].

Questions such as ´´What are the rock formations that might be suitable for storage?´´ A key mechanism for storing CO_2 in deep geologic formations and ensuring that it stays there is a system of layered, deeply buried, permeable rock formations that serve as the CO_2 storage reservoir, overlain by impermeable caprocks which serve to keep the injected CO_2 in place. A thorough evaluation of these formations and their ability to accept and retain injected CO_2 must be an essential component of site assessment before any CO_2 is injected. Here we take a closer look at these formations in the broad area of Portugal and try to match the potential sites with the greater CO_2 emissions power plants. At a properly designed and well-managed CO_2 storage site, the chance of CO_2 leakage should be small; thus, concerns about catastrophic release are likely unfounded.

2. Geological formations suitable for storing CO_2

The capture and storage of CO_2 in geological formations is considered, by the scientific community, to be as one of the main ways to reduce greenhouse gas emissions. Regarding the geological storage capacity in Portugal, the results show that there are suitable geological formations that can be used as CO_2 storage sites. Particularly, the results have shown that CO_2 can be stored in oil fields and deep saline aquifers.

Mainland Portugal has four large morpho-structural units: the Hesperic Massif (or Iberian Massif or Ancient Massif), the Occidental Mesocenozoic Border, the Meridional Mesocenozoic Border and the Tertiary Basins of Tejo and Sado. The resultant seismic and gravity data allowed a better delineation of the Mesocenozoic sedimentary basins. These can be grouped into inner basins, which are located in the inner part of the continental margin and often extending onshore, and outer basins, which are mostly located in deeper waters to the west and south of the former. The inner basins are the Oporto Basin, the Lusitanian Basin and the Algarve Basin. The outer basins are the Galicia Interior Basin, the Peniche Basin, the Alentejo Basin, the Sagres Basin and the Gulf of Cadiz Basin (DPEP, 2008). These are presented in the Figure 1.



Figures 1. Portuguese inner (a) and outer (b) Mesocenozoic sedimentary basins [2].

The potential geological storage locations considered in this work are the deep saline aquifers [3]. The National Institute of Engineering, Technology and Innovation (INETI – Instituto Nacional de Engenharia, Tecnologia e Inovação) presented a preliminary study for CO_2 storage in deep saline aquifers. The geological formations identified in these studies are presented in the next Figure 2.

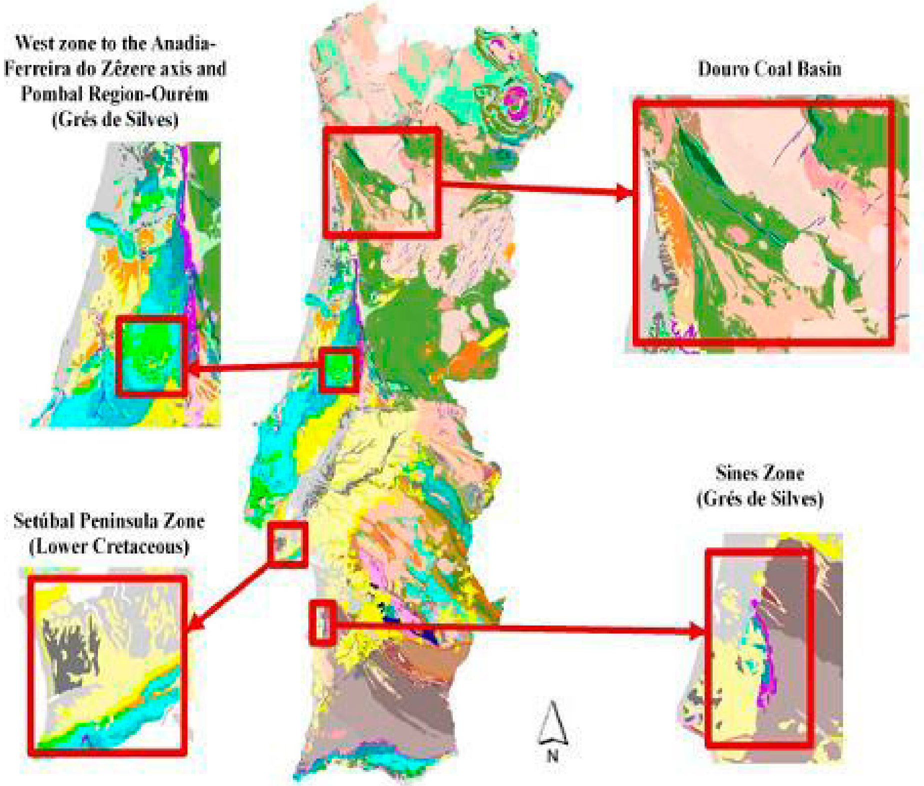


Figure 2. Geological formations identified in the INETI preliminary study as potential sites for CO_2 storage [3] and Douro coalfield basin

The main geological indicators that determine the suitability of a deep saline aquifer as a storage site are reservoir depth, thickness, porosity, permeability, seal integrity and salinity [4].

Saline formations are deep sedimentary rocks saturated with formation waters or brines containing high concentration of dissolved salts. Due to the high salt concentration, these waters are unsuitable for agriculture and human consumption. However, the estimation of the storage capacity in deep saline formations is not simple because of the multiplicity, complexity and interactions of mechanisms that occur to store CO_2 in these formations. Among these mechanisms are physical trapping beneath low permeability caprock, dissolution and mineralization. They occur simultaneously and on different time scales. These reasons result in a main focus on physical trapping mechanisms and/or dissolution in the majority of estimates of CO_2 capacity storage in deep saline formations, making a simplifying assumption that no geochemical reactions occur simultaneous with CO_2 injection, flow and dissolution [1].

Saline aquifers are here defined as those whose water improper for any use, given its content in salts. For purposes of selection of potential targets the various processes that have been considered for storage in saline aquifers are (1) storage in structural traps; (2) dissolution of CO2 in the saline aquifer fluid; and (3) replacement of the reservoir fluid by CO2, hydrodynamic conditions permitting.

A preliminary screening excludes the pre-Mesozoic basement, in view of its crystalline nature, with fissure permeability, which is not large in general and decreases markedly with depth. Additionally, fissure aquifers are usually not properly confined. Therefore our target areas are the Meso-Cenozoic West and South basins. Concerning the South Meso-Cenozoic basin, there are no onshore favourable conditions, given that the existing aquifers are tapped for human use or crop watering. Saline aquifers in this zone (not identified) will be small and will exhibit low porosity and low permeability. In the offshore there will probably exist saline aquifers in Jurassic formations (both in the Lower-Middle Jurassic and in Upper Jurassic). The Western Meso-Cenozoic formations, in particular those within the basin between Alcobaça and Arruda dos Vinhos, are the most promising. It is highly likely that the thickest part of this basin contains deep saline aquifers in the Lower and Middle Jurassic formations (the Upper Jurassic formations contain water of good quality). In a first approximation the fact that the structure is synclinal is unfavourable. However, it is possible that the aquifer may be limited by sealing faults. A possibility of a more detailed analysis could lead to definition of more favourable sub-domains. The Aveiro Cretaceous aquifer system is composed of several aquifer beds, including some that are not exploited because they contain high salinity waters. These saline aquifers may also be considered as possible targets, if migration of CO_2 into the freshwater aquifers can be prevented. This migration would be a disaster, as these freshwater aquifers are extremely important. The Tertiary Tagus Basin contains Portugal's most important aquifer system. It also includes, in its deeper parts, high salinity waters that should be considered for CO_2 geological saquestration.

3. Geological Site selection and Source sink matching

One of the most cost effective factors in minimizing leakage and ensure safety of geological CO_2 storage is site selection. Subsurface characterization is a fundamental step in identifying potential geological units for CO_2 storage. While some degree of uncertainty is enevitable when characterizing the subsurface because of inherent natural variability, three elements are essential for geological storage to be technically feasible. The potential storage unit must have sufficient pore volume to store all the injected material (capacity); the formation characteristics must allow near well bore (injectivity); and an overlying sealing package must ensure the containment of appropriate fluids (containment). In general it is best if the site allows for CO_2 to be stored at depths below 800-1000 meters where CO_2 is compressed to a super dense phase which enhances both the storage capacity and the containment ability.

A detailed source-sink matching is crucial to understanding the relationship between the emissions sources and the storage opportunities in order to assess the impact of CCS on emissions reduction and what the role of CCS could be among other mitigation options. A good relationship between sources and sinks leads to the possibility of significant reduction of the amount of the CO_2 emissions from these sources. However and as stated in the IPCC Special Report on CCS, if CO_2 sources and sinks "are not well matched geographically, then there will be implications for the length and size of the transmission infrastructure that is required, and this could impact significantly on the cost of CO2 capture and storage, and on the potential to achieve deep reductions in global CO_2 emissions" [1].

Then, the analysis of the hypotheses for the implementation of CCS systems in mainland Portugal based on source-sink matching was performed, considering only the proximity of the sources and storage sites. A cost estimation for a CCS system in mainland Portugal, considering only CO_2 capture, transport and storage, was also attempted.

The major part of the CO_2 emissions comes from the electricity production sector, and therefore it is the logical sector to press and act in order to reduce the emissions. The Portuguese industrial system was studied and further analyzed with its major industrial CO_2 sources being characterized and grouped by clusters, showing the emissions location and intensity (Figure 3). The IPCC Special Report on CCS defined large stationary CO_2 sources processing at least 0.1 Tg CO_2 per year as key criteria for economically feasibility of capture technology. Installations figured in this map created by ArcGIS software were identified under this condition. Classification of the large point CO_2 emitters was based on the installations included in the National Allocation Plan II for Portugal and the evaluations of the corresponding emissions were estimated from the technical characteristics of each plant [5].

The yellow color in Figure 3 below represents fossil fuel power plants. Portugal has got presently seven thermal power plants. Two of them use pulverized coal (PC), three of them use natural gas in a combined cycle (NGCC) and the remaining two use fuel-oil for combustion. Characteristics of these power plants are summarized in Table 1.

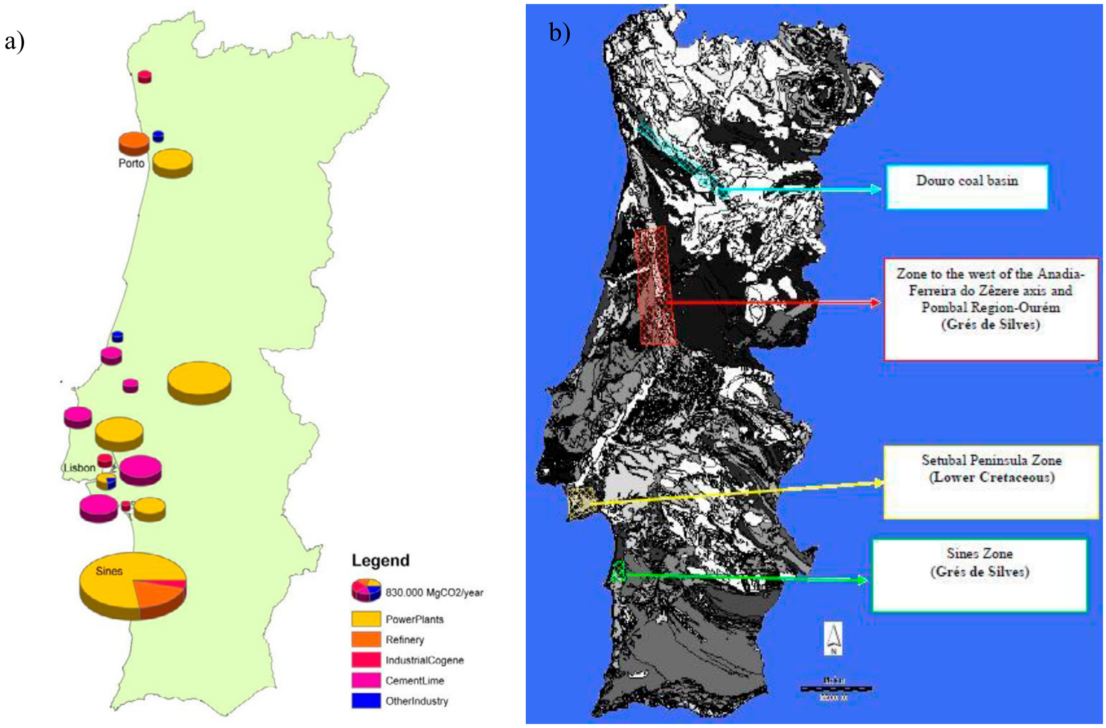


Figure 3. Major industrial CO_2 sources characterized by clusters (CO_2 emissions higher than 0.1 Tg per year, data based on year 2006, [6]) (a) matched with location of the potential geological sinks in mainland Portugal (b).

This study focuses mainly on power plants combusting coal, since they are a greater source of CO_2 than a natural gas power plant. This is due to the different heating value of the fuels, and to the different molecular weight of the fuels. Also as it is possible to see in Table 1, the NGCC technologies have higher efficiency than the power plants combusting pulverized coal, therefore the coal power plant will cause larger impact in CO_2 emissions.

Table 1 – Characteristics of existing fossil fuel power plants in Portugal.

	Combustion technology	Installed capacity (MWh)	Efficiency (%)	Emissions ($MtCO_2$/year) in 2006
Sines	PC	1256	0,39	8,73
Pego	PC	628	0,43	3,96
Ribatejo	NGCC	1176	0,55	2,07
Tapada do Outeiro	NGCC	990	0,55	1,54
Lares	NGCC	862	0,55	n.a.
Carregado	Fueloil	750	0,38	0,19
Setúbal	Fueloil	946	0,40	0,97

PC –Pulverized coal
NGCC – Natural Gas Combine Cycle
n.a. – Power plant in Lares started operation in 2010.

4. Methods and results regarding the CO_2 Storage and Transportation costs

The costs of transport and storage are much lower than the costs of capture [7]. The determination of CO_2 transport and storage costs depends on the mean of transportation, on the distance of the CO_2 source to the storage location and on the characteristics of the storage reservoir. Pipeline costs can be divided into construction costs, operation and maintenance costs (including monitoring), and other costs like design, fees and rights-of-way. The transport costs differ between onshore and offshore pipelines, the latter often being about 40% to 70% more costly than the former. Onshore pipeline transport costs depend significantly on the terrain characteristics as they could increase by 50% to 100% or more if the route is congested and heavily populated. Assuming that the CO_2 will be transported via land-based pipelines, as this is a common via to transport this and other gases, costs like the pipeline diameter and construction issues like circuitous routing and terrain characteristics have to be considered in the overall CO_2 transport costs. From the natural gas pipeline land construction experience, the capital costs for transport pipelines are in the order of $40 000/mile per inch of pipeline diameter [8].

Scenario 1: Storage and Transportation of CO_2 from Sines Zone power plant to the west of the Anadia-Ferreira do Zêzere axis and Pombal Region-Ourém saline aquifer

The main capital costs of CO_2 geological storage are drilling wells, infrastructure and project management, while operating costs include manpower, fuel and maintenance. The injection costs depend mainly on drilling wells and operational costs. Storage costs are largely influenced by the number of required wells, which depends on the injectivity and the allowed overpressure, and the years of operation. However, these costs are site-specific, depending on the type of reservoir, location, depth and other characteristics of the storage reservoir formation. The main items of CO_2 storage in saline formations are reservoir and injection characteristics like permeability, thickness and depth that affect injection rates and well costs. It has been estimated in Europe that cost estimations for CO_2 geological storage in onshore saline formations for depths of 1000-3000 m are between 1.9-6.2 US$/t$CO_2$ stored, the most likely value being 2.8US$/t$CO_2$ stored [1]. The IPCC Special Report on Carbon Capture and Storage (SRCCS) cited three studies as the basis for their estimates of aquifer storage costs, which ranged from $0.2 to $6.2 per tonne CO_2 excluding monitoring, verification & closure costs.

Here in this study and in this first scenario, the CO_2 emissions that come from the Sines Power (Table 1) will be stored in the West of the Anadia-ferreira do Zezere axis and Pombal Region-Ourem saline aquifer (Figure 3). The CO_2 quantities emitted from the Sines power plant are 8.73 million tonnes per year (Table 1) while chracteristics of the storage location of The Lusitanian basin expands from the onshore to the offshore with a total area of about 22000 km^2 and a maximum sedimentary thickness of about 6km. As far as the authors are aware, unitl now there are no generally accepted standards and methodologies to calculate and even estimate the CO_2 storage capacity of a formation, structure, basin, area, country and even at worldwide level. Thus when calculating capacity, several types of estimates can and often are made, depending on the nature and purpose of the assessment and they all lie across different regions of the resource pyramid [9]. This pyramid considers three technical and economic categories named Theoretical, Realistic and Viable Capacity. In this case for the capacity calculations in saline formations it has been used the volumetric approach using the Formula 1 of Brook et al [9]:

$$M = S\ x\ h\ x\ p\ x\ F \tag{1}$$

Where M is calculated capacity, S is area, H is thickness, P is porosity and F is sweep coefficient. The most important was to assess the value of the sweep coefficient, because this item by decisive fashion can influence the final results. Ambiguities in volume of aquifer and density of gas are not so ´´dangerous´´; assessment of porosities is more decisive. For that reason we have made an assumtpion and utilised a porosity factor of 0.2 which is an average value used also in other reports while the thickness of the surface area is ranged between 150 and 450 meters thus considering an average of 200 m. As in other reports the sweep cofficient is considered 0.4 (rule-of-thumb approach), thus from the formula above the calculated capacity in this case is 352 Mton of CO2. From the abovementioned data in Table 1 and supposing that the emissions will remain in this level and the power station will still remain in operation the next years, the saline aquifer is capable to store CO_2 for 40 years. With an average injection CO2 rate of 2000 ton/day then this emans that it would require a total time of 176 days to have the reservoir fulled in 40 years period of time.

The length of the pipelines was determined in *Google Earth* calculating the approximate linear distance between the CO_2 source emissions and the correspondent storage area, which was considered the CO_2 injection point. Thus the onshore pipeline length and diameter is estimated at 50 Km and 70 cm (due to the annual CO_2 volume of more than 2 Mt CO2/year according to REN, rrespectively [10], while its investment costs, according to methodology proposed by IEAGHG, calculated to be 35.0 million $ [11]. Generally, the pipeline investment cost depends on the topography and the ground conditions while in our scenarios the cost of the pipeline is calculated for flat terrain. Supposing that the initial capital is 40% of the total cost, the depreciation time is 25 years and the interest rate is 5% the annual charge is 1750000 $. According the aforesaid information the storage cost is estimated at 0.40$/t of CO_2 (0.20$/t CO_2/100km).

Conclusions

Given the very large volume of CO_2 that will need to be transported from the thermal power plants, located in the soutn of Portugal to the sequestration geological site to the middle of Portugal, saline aquafers with pipelines are the only practical methods that seem to have transportation costs that are very similar with the ones propose by the literature. According to the International Energy Agency, the transportation cost ranges from 1 to 10 $/t$CO_2$. However, the transportation costs of CO_2 are considered to be small compared to the capture costs (around 40 $/t CO_2) depend mainly on the capture technology.

Further studies by several authors have put forth that sea floor rocks, both sediments and basalts, may constitute excellent reservoirs for CO_2, given that (1) they are extremely large saline aquifers; and (2) in areas of hydrothermal activity (focussed or diffuse) the presence of basaltic rocks at temperatures above 50ºC may favour storage as carbonates of Ca, Fe, and Mg, certainly the safest and more definitive form of CO_2 sequestration. In the view of several ZeroEm researchers, this is the most promising solution.

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